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(71) Applicant (*for all designated States except US*): CALIMETRICS, INC. [US/US]; 5901 Christie Avenue #406, Emeryville, CA 94608-1936 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): McDERMOTT, Gregory, A. [US/US]; 94 Webster Street, San Francisco, CA 94117 (US). WONG, Terrence, L. [US/US]; 1845 Pacific Avenue #5, San Francisco, CA 94109 (US). O'NEILL, Michael, P. [US/US]; 1652 Santa Clara Street, Richmond, CA 94804 (US). PIETRZYK, Cezary [PL/US]; 614 Major Vista Court, Pinole, CA 94564 (US). JOHNSON, Bruce, V. [US/US]; Apartment 22J, 3040 Smyth Road, Berkeley, CA 94704 (US). SPIELMAN, Steven, R. [US/US]; 2032 Delaware Street #9, Berkeley, CA 94709 (US). SHAFAAT, Sayed, Tariq [US/US]; 585 East Dolphin Drive, Freeland, WA 98249 (US). BUSTILLO, James, M. [US/US]; 18396 Magee Way, Castro Valley, CA 94596 (US).

(74) Agents: WEAVER, Jeffrey, K. et al.; Hickman Beyer & Weaver, P.O. Box 61059, Palo Alto, CA 94306 (US).

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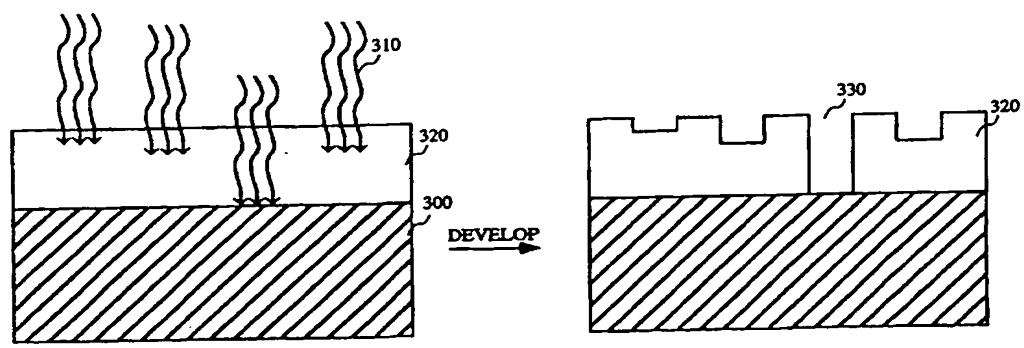

(57) Abstract

An apparatus (figure 2) and method for forming a digital optical disc master from a disc having a substrate (300) coated with a photoresist coating (320). The method includes irradiating the surface of the photoresist material (320) with a laser beam (310) at a multiplicity of pit locations over the substrate (300) causing the photoresist material (320) to react to the laser radiation (310) to form at least three different discrete levels at the multiplicity of pit locations relative to the surface of the substrate (300) due to the dose of radiation applied being calculated to react with the photoresist to a depth equivalent to the discrete levels. The exposed photoresist is then developed to achieve the pits having the different discrete levels. A further method is disclosed for equalization and compensation for intersymbol interference between adjacent pits.

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Apparatus and Methods for forming and use with variable pit depth optical recording media

BACKGROUND OF THE INVENTION

The present invention relates generally to a method and apparatus for mastering a compact disc with multiple level pits. Specifically, a method and apparatus are disclosed for creating a layer of photoresist of a depth that is precisely controlled so that more than two levels of pits varying within approximately one quarter wavelength of the reading laser light are created. In one embodiment, a method and apparatus for intersymbol interference compensation that compensates for intersymbol interference between different depth pits is further disclosed.

In a compact disc (CD and CD-ROM), information is stored on the surface of a disc as pits which are read by a laser. The pits are transferred to the plastic surface by a metal stamper which is produced, through a series of intermediates, from a master. The information is transferred to the master during the mastering process. The mastering process involves using a focused laser beam to record the information onto a thin layer, generally about 150 nm thick, of photosensitive material deposited onto a glass substrate. The photosensitive material can be positive photoresist or a thermally ablative medium (so-called "Direct Mastering"). Photoresist is, however, currently the most common medium used for mastering. Exposing a thin photoresist film on a rotating substrate with a focused and intensity-modulated laser beam, and subsequent development, results in a pit pattern arranged in a spiral track on the disc. After development, the minute areas of exposed photoresist are washed away, leaving the series of holes, or pits if positive photoresist is used. A detailed description of this method is described in "Videodisc and Optical Memory Systems" by Jordan Isailovic .

FIGURES 1A through 1L are schematic diagrams illustrating how polycarbonate optical discs are produced. First, a glass disc 100 is coated with a photoresist coating 102. Photoresist coating 102 is shown as a positive photoresist so that, as the photoresist is

exposed to light, it softens and becomes susceptible to being etched away during a development process. As a result of the radiation of certain portions of the disc by a laser, softened portions of photoresist 104 are created in photoresist coating 102. Softened portions 104 are removed during the development process and metal is deposited over the resulting contour of the disc that is formed. A metal father 108 is formed according to the contours of metal deposition layer 106, and metal father 108 is separated from compact disc master 110. The compact disc master 110 is usually destroyed in the process of removing it from metal father 108. Next, the metal father is used to produce a series of metal mothers 112. Each metal mother may then be used to form a stamper 114. The stamper is then used to stamp a polycarbonate plastic substance 115 into the form of a disc 116 in a molding process. Once stamper 114 is removed from disc 116, disc 116 is coated with a reflective metal coating 118 and then a protective plastic layer 120 is deposited over the surface of disc 116. Protective plastic layer 120 functions to protect the pits from being damaged.

The above process has been described for a positive photoresist. However, it should be noted that a negative photoresist could alternatively be used, in which case a dose of laser energy would be required to harden the photoresist and prevent it from being etched in a development step. Areas of the disc which do not receive the dose of laser energy would contain photoresist which is not fully hardened and would be etched away during the development process.

In the example shown, the master disc is used to create a negative disc, i.e., a disc which has bumps in locations which correspond to pits in the compact disc being produced. The father disc creates a series of mother discs which have pits corresponding to the master and the final compact disc which is being produced. The mother creates a stamper which is a negative of the master and finally, the stamper creates the compact disc which has pits that correspond to the pits created in the master disc.

Current methods of optical data storage encode information on the surface of a CD using pits of constant depth but varying length alternating with lands on the surface of the disc. The length of the pits and lands encode the data. An optical detector reads the data and outputs a signal corresponding to a pit or land. Each edge or transition from pit to land or land to pit is detected and recognized as a logical 1. The length of flat pit or land between edges represents a

series of logical 0's, and the number of zeroes in the series is proportional to the length of the flat region between edges.

More information could be stored on the same amount of CD surface area if, instead of merely detecting edge transitions between pit and land, a CD reader could detect multiple levels of pits. For example, if eight different levels of pits could be distinguished, then three bits of information could be stored in the area of a minimum-length pit (16 different levels would encode four bits, 32 levels would encode five bits, and so on). To further increase the information capacity of the CD, rather than following a variable-depth pit by a land region, another variable-depth pit could immediately follow the preceding one, and so on, so that each variable-depth pit immediately abuts each adjacent variable-depth pit. An optical disc that stores more than one bit of information at each pit or symbol location by modulating the depth of the pits is referred to as a pit depth modulated (PDM) disc.

A method of mastering pits of variable depth would be necessary in order to allow the density and data-rate speed increases afforded by a variable depth pit scheme such as mentioned above. A multistep mastering method for variable depth pits is described in U.S. Patent No. 5,235,587, issued August 10, 1993, to Bearden, et al. This method suffers from the need to do multiple mastering steps, one step for each depth of pit desired, which is undesirable. It would be advantageous if mastering of variable-depth pits could be done in a single mastering step and if mastering variable-depth pits could be accomplished using the same photoresist and mastering benches used commonly today in mastering CD's. It would furthermore be desirable if such pits could be read by currently available optical readers with minimal modification.

U.S. Patent No. 4,150,398, issued to Kojima, et al. describes a single step mastering process suitable for use in storing analog signals on a disc using photoresist. Kojima, et al. describes a photo-sensitive recording medium which is photo -reacted to a degree varying substantially linearly in correspondence with the intensity of the light incident on the medium over a range of light intensities. The intensity of the light beam and the degree of modulation of the light beam by the signals are selected to maintain the maximum and minimum intensities of the modulated light beam within a predetermined range so as to form simultaneously on the record medium a tracking path portion and recorded signal portion. The range of depth of the reacted photoresist described in Kojima, et al. is between 200 nm and 800 nm.

Discs mastered according to the teaching of Kojima, et al. are not readable by optical disc readers. Current optical readers detect an intensity difference which results from the interference of light reflected from the bottom of each pit with light reflected from the surrounding disc surface. When the depth of the pits is one quarter of the wavelength of the light used to read the disc, then light reflected from the bottom of the pit interferes destructively with light reflected from the disc surface so that the decrease in the intensity of the reflected light may be detected. The wavelength of the laser used by most detectors is 780 nm. Since the index of refraction of the plastic used in most compact discs is approximately 1.55, the wavelength of light in the plastic is approximately 500 nm. One quarter of a wavelength is therefore a distance of about 125 nm. Kojima's minimum displacement distance of 200 nm to reach the linear region of the photoresist characteristic curve is therefore greater than one quarter of the wavelength of the laser used to read the optical disc.

The overall dynamic range of depth change taught by Kojima, et al. of between 200 nm and 800 nm is also greater than one quarter wavelength. Generally, Kojima, et al. does not address the problem of creating multiple level pits less than one quarter of a wavelength deep in a repeatable manner. Kojima, et al. teaches using a photoresist with a steeply varying linear characteristic curve over a predetermined dynamic range. Kojima, et al. does not teach how the coating and development process may be engineered to enable the repeatable production of discrete level pits.

Current optical disc mastering using photoresist processing likewise does not produce precisely controlled multiple pit levels. Current optical discs are produced from masters which are created from photoresist coated discs. A single desirable pit depth is chosen which is less than one quarter of a wavelength. The photoresist is exposed by a laser beam intensity that is modulated by cycling from a fixed maximum power to off, basically an "on or off" mechanism. Although a pit depth of exactly one quarter of a wavelength would create complete destructive interference for reflected light and therefore optimum contrast at the reader with neighboring lands, a somewhat smaller pit depth level is generally selected to provide a better tracking signal. Also, it should be noted that in the stamping process, the depth of pits formed is slightly less than the actual depth of the pits on the master. The thickness of the photoresist layer is typically approximately 150 nm and essentially all of the photoresist is removed to create a pit or none of the photoresist is removed to leave a land. Other thicknesses of photoresist are possible. No attempt is made to precisely remove intermediate amounts of

photoresist at surface portions adjacent to other surface portions which have photoresist removed to a different level.

As pits are stored more and more closely together on a CD, Intersymbol interference (ISI) occurs on both conventional CD's as well as PDM discs. Light reflected from one pit also tends to interfere with light reflected from another pit, especially when the pits are smaller than the reading laser spot of the optic stylus, resulting in intersymbol interference. The depth and location of one pit or symbol, therefore, tends to influence or interfere with the signal that is read from neighboring signals. The effect of the interference is greater when the symbols are closer together. As the spatial frequency of the pits increases, (as it must when more pits are included in a given area to increase data storage density), the intersymbol interference effect increases. A "modulation transfer function" (MTF) describes the transformation of the detected signal that results from the diffraction of light from neighboring pits.

Optical data disc readers currently use analog filtering of the detector signal to equalize the frequency response of the system. The equalization is an attempt to compensate for the MTF, which predicts how much contrast an optical imaging system will generate when scanning different spatial frequencies. Current art uses a simple frequency equalization as discussed in chapter 2 of Principles of Optical Disc Systems (Bouwhuis, Braat, Huijser, Pasman, van Rosmalen, and Immink, 1985, Adam Hilger Ltd., Boston, MA).

Generally, the magnitude of the MTF decreases monotonically with increasing spatial frequency, reaching zero at a limit called the optical cutoff frequency. For example, the peak-to-peak signal from a series of 0.83 μm pits and lands on a CD is approximately 40% that from 1.6 μm marks. Above the cutoff frequency, which for CD corresponds to 0.43 μm pits and lands, a CD reader would detect no contrast at all. Since the shorter marks correspond to higher temporal frequencies in the detector signal, one can "equalize" the contrasts of long and short marks by increasing the high-frequency gain in the electronics.

Current analog equalization filters are a limited solution for three reasons. First, it is difficult to build a filter which accurately inverts the MTF over a wide frequency range. Second, optical disc reading systems are nonlinear, and there is a complex interaction between the reading spot of the optical stylus and the pits or marks on an optical disc. Third, because such an analog filter cannot be adjusted, the linear velocity of the disc must remain fixed. This is because the filter reacts to the timing of the electrical signal whereas the ISI really is a

function of distance along the track. If the linear velocity is not constant, then the relationship between spatial frequency and temporal frequency changes. Consequently, CD's and DVD's are constant linear velocity (CLV) systems. CLV is inconvenient for data storage because the spindle speed must be adjusted each time the drive seeks data at a different disc radius. When the reader head seeks information at a different radius, the drive must wait for the spindle to change rotational speed to maintain the linear velocity. Certain magneto-optical drives use analog equalization filters and operate at CAV. This is accomplished by dividing the disc radially into several zones, each with its own data rate and equalization filter. The zones must be narrow enough so that the change in linear velocity is small enough over a single zone so that one filter can operate over an entire zone even though the linear velocity is changing.

To maximize the information density on an optical disc, the symbols are made as short as possible, leading to increased inter-symbol interference. ISI limits the capacity of conventional binary discs (CD, DVD) and is particularly harmful to the signal from a PDM disc with multi-level marks. If ISI could be removed more effectively than analog equalization techniques, smaller symbols could be used and higher capacity and transfer rates could be achieved.

In view of the foregoing, it would be desirable if the depth of photoresist removed during the development process could be precisely varied to achieve different discrete pit levels within a range of less than 125 nm, or a range corresponding to one quarter of the wavelength of the light which is to be used to read the disc. Furthermore, there is a need for methods and apparatuses for providing better equalization filters than those that are currently available. Specifically, it would be desirable if equalization filters could be developed which could adapt to different linear speeds so that nonconstant linear velocity disc drive systems could be used. In addition, there is a need for methods and apparatuses for precompensating for the linear, nonlinear, and other effects which are caused by pit depth modulation. Also, it would be desirable if the pit depth modulation of a PDM disc could be designed to precompensate for all or part of intersymbol interference.

SUMMARY OF THE INVENTION

Accordingly, the present invention provides apparatuses and methods for fabricating an optical disc master, for equalization, and for precompensation to correct for intersymbol interference. In one embodiment, The data levels to be stored on the disc are determined and a substrate is coated with a layer of photoresist material. A variable power laser beam irradiates the photoresist in a way which causes the photoresist to be partially exposed to a depth corresponding to the data level being represented. Controlled development of the photoresist allows repeatable pit levels to be formed.

In another embodiment, a method of compensating for intersymbol interference on an optical disc is provided. The method includes measuring an intersymbol linear transfer function. The intersymbol linear transfer function substantially describes a linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc. The intersymbol linear transfer function is convolved with a write signal to produce a linearly transformed portion of the optically detected read signal. An inverse linear transfer function of the intersymbol linear transfer function is determined. The inverse linear transfer function has the property of canceling the effect of convolving the intersymbol linear transfer function with the write signal. The optically detected read signal is convolved with the inverse linear transfer function. Thus, the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled by the convolution of the optically detected read signal with the inverse linear transfer function.

In another embodiment, a method of compensating for intersymbol interference is disclosed that includes measuring an intersymbol linear transfer function that substantially describes the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc. The intersymbol linear transfer function is convolved with a write signal to produce a linearly transformed portion of the optically detected read signal. An inverse linear transfer function of the intersymbol linear transfer function is determined. The inverse linear transfer function has the property of canceling the effect of convolving the intersymbol linear transfer function with the write signal. The inverse linear transfer function is divided into a short portion and a long portion. The write signal is convolved with a precompensation transfer function and the precompensation transfer function is substantially the inverse of the long portion of the inverse linear transfer function. The optically detected

read signal is convolved with the short portion of the inverse linear transfer function so that the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

In another embodiment, a method of compensating for intersymbol interference on an optical disc is disclosed that includes measuring an intersymbol nonlinear transfer function. The intersymbol nonlinear transfer function substantially describes the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc. The intersymbol nonlinear transfer function is nonlinearly convolved with a write signal to produce a nonlinearly transformed portion of the optically detected read signal. An inverse nonlinear transfer function of the intersymbol nonlinear transfer function is determined. The inverse nonlinear transfer function has the property of canceling the effect of nonlinearly convolving the intersymbol nonlinear transfer function with the write signal. The write signal is nonlinearly convolved with a precompensation transfer function and the precompensation transfer function is substantially the same as the inverse nonlinear transfer function so that the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

These and other features and advantages of the present invention will be presented in more detail in the following specification of the invention and the accompanying figures which illustrate by way of example the principles of the invention. These and other features and advantages of the present invention will be presented in more detail in the following specification of the invention and the accompanying figures which illustrate by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURES 1A through 1L are schematic diagrams illustrating how polycarbonate optical discs are produced.

FIGURE 2 is a schematic diagram of a variable exposure system used to create multilevel pits on an optical disc.

FIGURE 3 is a schematic diagram illustrating the exposure of a photoresist layer.

FIGURE 4 is a graph illustrating a laser power modulation curve.

FIGURE 5A is a graph illustrating residual photoresist after development plotted against exposure time for different development times.

FIGURE 5B is a graph illustrating residual photoresist after development plotted against exposure time when undiluted developer was used.

FIGURE 5C is a graph illustrating residual photoresist after development plotted against exposure time when developer that was diluted 50% (1:1) was used.

FIGURE 6 is a graph illustrating exposure energy versus pit depth for one embodiment.

FIGURE 7 is a graph illustrating a plot of bump height (in nm) verses cutting laser power (in mW) taken from two different runs of AFM analysis of stampers produced by the procedure outlined in the embodiment below.

FIGURE 8 is a block diagram which illustrates an optical data storage and data recovery system.

FIGURE 9 is a graph which illustrates Fraunhofer diffraction results for 0.5 μm length pits on a 0.5 μm wide track.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the preferred embodiment of the invention. An example of the preferred embodiment is illustrated in the accompanying drawings. While the invention will be described in conjunction with that preferred embodiment, it will be understood that it is not intended to limit the invention to one preferred embodiment. On the contrary, it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims.

The present invention provides an apparatus and method for mastering variable-depth pits in photoresist media by using a laser beam to expose the photoresist by scanning across the disc as the disc rotates and by controlling the development of the photoresist on the disc. The present invention further provides an apparatus and method for providing equalization and for compensating for intersymbol interference when pits on an optical disc are read.

Variable-depth pits are produced in photoresist media by providing a different type of modulation to the laser beam than is used currently to master compact discs. The method used in a preferred embodiment involves modulating the power of the laser to intermediate power levels between a maximum power and no power. Pits of different depth are defined by the photoresist in areas that are exposed to the intermediate power levels of the laser. By careful control of the power level and the development procedure, the different depth pits are defined in a reproducible manner. In certain embodiments, the modulation of the power level is further controlled to provide precompensation for intersymbol interference between variable depth pits.

FIGURE 2 is a schematic diagram of a variable exposure system used to create multilevel pits on an optical disc. A laser 200 provides a laser beam 212 that exposes the photoresist. An acousto-optical modulator 210 modulates the strength of the laser beam so that the beam variably exposes the surface of the disc. An electro-optical modulator is also used in certain embodiments. An optical system 220 focuses the laser beam onto the surface of disc 230 which is spinning about a central axis 234. Acousto-optical modulator 210 is controlled by a modulation source 240. Modulation source 240 computes the desired pit depth and outputs a control signal to acousto-optical modulator 210 so that the appropriate intensity of light irradiates disc 230 at each pit location. In certain embodiments, modulation source 240 determines a pit depth that also compensates for intersymbol interference. In order to properly control the light intensity, the intensity of laser beam 212 is measured at some point after the

beam travels through modulator 210. In one embodiment, a detector 242 is used to measure the intensity just before the beam enters optical system 220.

In the preferred embodiment, pit levels are determined based on the amount of information to be stored in each pit and the characteristics of the reading device which is reading the data. In one embodiment, 3 bits of information are to be stored in each pit, and 8 different data levels are determined. In another embodiment 2 bits of information are stored in each pit and 4 different data levels are determined. In general, greater than two bits of information are stored at each pit. It should be noted that numbers of data levels such as 10 which represent a fractional number of bits are allowed. Those data levels are then mapped to output levels of the reading device. Pit depth levels are determined which will produce the output levels. An amount of laser energy which will expose the photoresist a sufficient amount to produce the desired pit depth level is determined. In the preferred embodiment, the laser energy which exposes the photoresist is varied by changing the laser power. Other embodiments change the amount of time that a single power laser exposes photoresist. This is accomplished by varying the rotation rate of the disc to vary the amount of time that disc portions are exposed to the laser beam. Alternatively, the laser beam is pulsed at a variable high frequency so that different disc portions receive different quantities of laser energy.

FIGURE 3 is a schematic diagram illustrating the exposure of a photoresist layer. A laser beam, 310, is allowed to expose portions of the photoresist layer, 320. This results, after controlled development, in variable depth pits 330. The photoresist layer, 320, is applied to a glass or plastic substrate 300 by traditional coating methods such as spin or dip coating. The thickness of layer 2 may be, but need not necessarily be the same as used traditionally in CD mastering, i.e. 120-170 nm. The thickness must be at least as thick as the deepest pit (approximately 170 nm in the preferred embodiment) required but may be thicker by 1 or more orders of magnitude. The type of photoresist could be either negative or positive. In a preferred embodiment, the photoresist is a positive photoresist such as that used currently in CD mastering, Shipley S1800 for example, but a photoresist such as Olin Ciba Geigy OCG 825, commonly used for IC manufacturing may also be used. It will be apparent to one of ordinary skill in the art that other photoresists may be used as well. The laser beam is allowed to expose the photoresist, and the amount of the photoresist that is exposed varies according to the power of the laser.

FIGURE 4 is a graph illustrating a laser power modulation curve. A laser power modulation curve 410 used in one embodiment of the invention is shown. Variable-depth pits are immediately followed by the preceding pit so that each variable-depth pit is immediately adjacent to other variable-depth pits. Laser power modulation curve 410 shows that there is no region of zero power except at the beginning and end of the pulse train. As a result, no land regions -- regions where the pit depth is zero -- are be formed. The absence of regions of zero power on laser power modulation curve 410 is not meant to imply that zero power regions cannot exist in the pulse sequence. A zero level may be used, and it is desirable in certain instances to include land regions between each pit, but it is not necessary to do so.

In a preferred embodiment, the development conditions of the exposed photoresist are controlled so that the desired pit levels may be precisely defined by the modulated laser power. Both the developer concentration and the development time are precisely controlled, as well as other parameters such as temperature, developer age and water purity. In one preferred embodiment, the temperature is controlled at 23 degrees C.

FIGURE 5A is a graph illustrating the residual amount of photoresist remaining after development versus the exposure time of the laser energy for three different development times. Curve 510 corresponds to a 30-second development time and has a relatively flat slope. Curve 520 corresponds to a 60-second development time and has a steeper slope. Curve 530 corresponds to a 120-second development time and has a much steeper slope than curve 510 or 520. This shows that if a shorter development time is used, it is possible to better control the variation in pit depth for a given variation in laser power. The concentration of the developer is also important . Typically concentration ranges from 0.1 to 0.3 Molar are acceptable. Concentration of 0.15 Molar is typically most preferred.

It should be noted that the exposure energy of the laser for each area of the disc was varied by varying exposure time of the laser. A similar curve would be expected if laser power were varied instead of exposure time, since total exposure energy controls the level of photoresist that is exposed. The exposure energy applied to the photoresist causes the photoresist to cross-link (negative photoresist) or depolymerize (positive photoresist) when the energy is absorbed. One preferred embodiment varies the exposure energy and affects a selected amount of photoresist by varying the laser power instead of varying exposure time. When the laser power is varied and there is some amount of noise in the signal which controls

laser power or noise otherwise created by the laser system itself, then it would be advisable to use a laser power versus pit depth slope which is relatively flat so that small variations in laser power do not create large variations in pit depth. This consideration may be balanced to some extent with constraints on the laser power and speed of the mastering process. One preferred embodiment varies the exposure energy and affects a selected amount of photoresist by varying the laser power instead of varying exposure time.

FIGURE 5B is a graph illustrating residual photoresist after development plotted against exposure time when undiluted developer was used. This results in the steeply sloped curves 540 and 550. Curve 540 is shown for no prebake of the photoresist, and curve 550 is shown for a 60-second prebake at 120°C. Again, the curves shown in FIGURE 5B were created by changing the total energy as a result of changing the exposure time. Similar curves would be expected if instead of changing the exposure time, the laser power were changed. The steepness of curves 540 and 550 is undesirable since small changes in the energy of the light used to expose the photoresist would create large changes in pit depth, making the system susceptible to noise in the laser power incident on the surface of the disc. Too steep a slope is undesirable because a very small change in the exposure energy will cause a large change in the pit depth.

FIGURE 5C is a graph illustrating residual photoresist after development plotted against exposure time when developer that was diluted 50% (1:1) was used. The slope of curve 560 and curve 570 are less than the slopes of curve 540 and curve 550 from Fig. 5C, however, the curve is noisier and more irregular. The irregular profiles are undesirable, since reproducible pit depths would be difficult to attain from such profiles. In accordance with the teaching of the present invention, a developer concentration should be chosen so that the residual photoresist versus exposure energy curve has sufficient slope so that a sufficient variance in pit levels may be obtained, but not so great a slope so that the change in pit depth with exposure energy is excessive. Care should also be taken that the exposure energy to residual photoresist curve does not have irregularities as shown in FIGURE 5C.

In one preferred embodiment for which results are illustrated in FIGURE 6, OCG 825 positive photoresist is spin coated onto a blank glass master at a thickness of approximately 1 μm. The prepared photoresist substrate is allowed to be exposed by an He-Cd laser operating at a wavelength of 442 nm. The laser is modulated by sending the laser beam through an

Acousto-Optic Modulator (AOM) which causes the exiting beam's intensity to be modulated based on the voltage applied to the AOM. Other methods of modulating the laser will be apparent to one of ordinary skill in the art. A lower applied voltage causes less light to be transmitted through and a higher voltage allows more light to be transmitted through the particular AOM system used. The laser is passed through an optical train to focus the beam to a small spot on the photoresist, about 5 μm in diameter in the present embodiment although a much smaller spot limited only by diffraction limits, can also be achieved. As the laser exposes the photoresist, a higher voltage is fed to the AOM when a deeper pit is desired and a lower voltage is applied when a shallower pit is desired. After the photoresist is exposed, there is an optional soft-baking step in which the photoresist is heated at a temperature of around 100 degrees C for a desired period of time. In the process that yielded the FIGURE 6 results, the softbake step was skipped. Next, the exposed photoresist was developed in an appropriate developer solution. An OCG 934 developer solution at a concentration of 2 parts developer to one part water was used and the photoresist was developed for 3 minutes and subsequently washed with distilled water for another 1 minute. The development process may be monitored spectroscopically for completion such as is done currently in the compact disc and IC industries. The developed photoresist was then hard-baked at 120 degrees C for 30 minutes, but no hard bake step is necessary.

The exposed photoresist sample produced by the above process was measured by Atomic Force Microscopy (AFM) to determine the depth of the pits produced in a 1μm thick photoresist. FIGURE 6 is a graph illustrating the depth of pits produced by this experiment versus the exposure energy per square centimeter. As shown, the process has been successfully designed so that the pit depth varies almost linearly with the exposure energy. A slope of approximately 20 nm per kJ/CM^2 was attained. Too great a slope tends to be vulnerable to noise and too small a slope tends to require too long for the mastering process. The exposure energy is determined by the linear speed of the scanning laser relative to the disc, the width, and the intensity of the beam. A mastering speed of 2.82 m/s may be used to master a disc in one hour. Slower mastering speeds use a lower power laser and provides sharper boundaries between pits, but require more time. A linear relationship such as the one obtained is desirable, but not required. As long as the exposure energy versus pit depth curve is reproducible, variable depth pits may be created by selecting the energy level that will produce the correct pit depth. It is therefore possible to vary the laser power to produce reproducible pit depths.

As shown above, the developer concentration, development time, type of development temperature, beam characteristics, depth of focus of beam, and scanning speed may all be varied in accordance with the present invention. In the preferred embodiment, the lands are not etched and the pits are exposed and etched to multiple levels between 0 and a distance approximately 1/4 of a wavelength of the laser that will read the disc. (If negative mastering were used, the pits and lands would be reversed.) Alternatively, all of the land regions could be exposed and etched to a certain level and the pit regions could be exposed and etched to vary between a distance of 0 and approximately 1/4 of a wavelength of the reading laser.

FIGURE 7 is a graph illustrating a plot of bump height (in nm) verses cutting laser power (in mW) taken from two different runs of Atomic Force Microscopy (AFM) analysis of stampers produced by the procedure outlined below for one preferred embodiment. A glass master was prepared by applying a photoresist coating, in this case Shipley Microposit 1400-5, to a thickness of 165 nm. The photoresist-coated glass was inserted into a commercial laser beam recorder (LBR), in this case one developed by Disc Manufacturing Inc. (DMI) which uses an Argon ion laser operating at 457.9 nm. A series of nominal 3T pits (0.8 μm long, 0.5 μm wide) were cut with a 50% duty cycle and 1.6 μm track pitch in a band 1 mm wide. The recording speed was 1.72 m/s. The laser power was set to different values in each band starting with 0.3 mW (the power was measured before the final microscope objective) going up to 1.4 mW. After laser cutting the glass master was developed using Shipley Microposit 352 developer.

After development the glass master was then metallized with Ni before going to the galvanics (formation of Ni parts) process from which a father, mother, and stamper was created. The stamper was subjected to AFM to measure the heights of the bumps (which are the negative image of pits on master) on the stamper. FIGURE 7 shows a plot of the data generated from these measurements. The heights of the bumps are plotted as a function of the laser power used to cut them. There is a substantially linear region between 0.3 -1.3 mW of recording laser power. This range of laser power corresponds in the system used to a energy incident on each region of between about 35 to 150 milliJoules per cm^2. This slope is approximately 169 nm/mW in one case and approximately 110 nm/mW in the second. It is estimated that at least 8 discrete pit levels could be defined within the depth range shown.

Thus a method and apparatus for creating multilevel pits on a master has been shown. A master created using the above method may be used to create a stamper for PDM CD's having multiple data levels. Once the desired data levels are chosen, the development parameters, laser power range, linear speed and beam characteristics are chosen in accordance with the present invention. A layer of photoresist is exposed to a variable amount of laser energy. The laser exposure energy is varied by varying the laser power or time during which the photoresist is exposed.

As noted above, as pits are stored more and more closely together on a CD, Intersymbol interference (ISI) occurs on both conventional CD's as well as PDM discs. Intersymbol interference is especially problematic for PDM discs which are detecting smaller signal changes than conventional CD's. In one embodiment, the present invention attacks the problem of reversing the effects of interference in two ways. First, to accurately cancel out linear effects, sophisticated filters for inverting the MTF are created using a digital signal processor (DSP). A DSP filter works by sampling and digitizing the signal at some rate and then mathematically convolving the signal data with a set of fixed coefficients. By choosing the coefficients, one can produce a filter with any desired frequency response, up to the Nyquist limit of 1/2 the sampling frequency. Second, a nonlinear mathematical algorithm is used to cancel out nonlinear intersymbol interference effects.

By using a DSP filter instead of an analog filter, the storage capacity of an optical disc system is improved in two ways. First, because a DSP filter will work over a wider frequency range, it is possible to operate closer to the cutoff frequency (i.e. use shorter marks). Second, the higher quality equalization allows for the decoding of multi-level marks, which requires better recovery of signal amplitudes than the decoding of binary marks. The speed of data recovery can also be improved since the DSP filter may be adjusted to work with a nonconstant velocity optical disc driver, eliminating the need to adjust the linear speed of the disc when different areas are accessed. Data recovery is further improved by removing nonlinear inter-symbol interference effects from the reader signal. The nonlinear techniques, which work in conjunction with DSP, are applied either as an extra signal processing step or as precompensation before the data is written. It is also possible, using precompensation that compensates for nonlinear and some linear effects, to simplify the DSP filter or to use an analog filter for the remaining linear effects.

Data is encoded as a groove of varying depth on the surface of a reflective disc. The data is first expressed as a series of multi-level symbols xi. Then, within the limits of the mastering and replication process, each symbol is converted into a segment of a groove with constant depth. These segments, called "pits", all have the same length. Although the term "pit" is used throughout this specification to refer to an area on the disc which represents a data symbol it should be noted that this invention is specifically not restricted to this particular surface morphology. A "pit" can be considered to be any type of multi-level mark, for example an area whose reflectivity has been modified by some sort of writing process or a mark with different possible widths.

Figure 8 is a block diagram which illustrates an optical data storage and data recovery system. A data signal 802 includes a sequence of symbols x_i received from the modulation encoder. The value of each x_i is one of M possible levels, so that a level is a real number denoting the value of a data symbol. Data signal 802 is fed to a precompensator 804 which precompensates the signal to help remove nonlinear intersymbol interference effects, and possibly some linear effects. The output of precompensator 804 is a signal 806 which represents the sequence of levels to be written w_i. The levels to be written w_i represent the precompensated levels which are to be written to the disc. These levels are not necessarily discrete.

Signal 806 is input to an Optical Disc Data Channel (ODDC) 808. ODDC 808 represents all steps in the process from disc mastering to reading which affect the data sequence that is recovered. Within ODDC 808, signal 806 is first transformed by an S-curve calibrator 810 which compensates for the responsiveness of the writeable disc medium to laser intensity. A one-to-one mapping converts each level w_i into the appropriate modulation signal for the mastering laser, taking into account the nonlinear response of all elements in the ODDC. S-curve calibrator 810 is designed so that if w_i is written to the disc as a very long pit, then $r_i = w_i$. The output of S-curve calibrator 810 is sent to a laser modulator 812 which controls a laser writing system 814.

The master disc which is produced by a laser writing system 814 undergoes disc mastering and replication 816 and a resulting profiled groove on the disc 818 represents the final optical storage form of the original data signal. An optical reader head 820 (for example a CD or DVD reader head) reads the disc and outputs a sampled reader signal 822, which is

denoted r_i. Reader signal 822 is input to a DSP deconvolver 824 which compensates for the MTF. Finally, the recovered levels 826, denoted as y_i are obtained. Recovered levels 826 are the convolution of s, the transfer function of the deconvolver, and r_i. Once the deconvolution is completed, except for noise and imperfections in the signal processing, y_i should equal the original data x_i. These values are passed on to the modulation decoder.

The precompensation and deconvolution steps implemented on precompensator 804 and DSP deconvolver 824 cancel out the Intersymbol Interference (ISI) from the Optical Disc Data Channel (ODDC), enabling successful recovery of the data. Precompensator 804 compensates for the nonlinear ISI effects and DSP deconvolver 824 compensates for the linear effects. Nonlinear effects are removed in the current preferred embodiment by precompensation to avoid the processing requirements of removing nonlinear ISI effects from the sampled reader signal, r_i. In other embodiments, nonlinear effects are removed after r_i is read.

In one embodiment, the design of precompensator 804 and DSP deconvolver 824 is based on a simulation of how the ODDC affects a sequence of symbols. The process of reading a disc was simulated using a model based on Fraunhofer diffraction theory. Such a simulation shows the inherent nonlinearity in the ODDC.

In one model, the data was encoded as a simple rectangular groove having a depth which changes at the start of new pits. The depths were chosen so as to produce evenly spaced signals when "read" by a simulated disc player. When the pits were shortened to as small as 0.5 μm the simulated reader signal exhibited ISI as expected.

Figure 9 is a graph which illustrates Fraunhofer diffraction results for 0.5 μm length pits on a 0.5 μm wide track. On the vertical axis, 1.0 represents the signal level from a flat area on the disc, and 0.0 represents zero reflected intensity. A curve 902 represents the track depth profile on the disc. A curve 904 represents a Fraunhofer simulation of the signal read by the optical disc reader. A set of samples 905 represent samples of curve 904 taken at various pit locations. A curve 906 represents the signal that would be expected from a linear system.

The dependence of the contrast of the signal on the spatial frequency is evident from Figure 9 on both curve 904 and 906. In the region between about 3 and 4 μm, the spatial frequency is relatively high and the contrast in the signal is reduced. In the region between

about 3 and 8 μm, the spatial frequency is relatively low and the contrast in the signal is at a maximum. In the region just past 8 μm, the spatial frequency is again higher and the contrast is lower.

As noted above, so long as a constant linear speed drive is used to read the disc, the spatial frequency maps to a temporal frequency in the read signal. A filter with an increased gain at higher frequencies could therefore compensate for the effect described above. However, when the linear speed of the reader head varies relative to the disc surface, as it would if a constant angular velocity (CAV) drive were used, then the spatial frequency would not map to the temporal frequency of the read signal. In certain embodiments, the present invention provides a digital filter which compensates for changing linear speeds to effectively filter the signal and remove linear ISI effects. The frequency response of a DSP filter is referenced to the data sampling clock, which by design is marking off specific distances on the disc. Such a filter could therefore remove ISI equally well at any linear velocity. It would therefore be possible to read a disc at CAV, reducing seek times.

As seen in Figure 9, the ISI has an unusual character. A deep mark amongst shallow neighbors produces a signal with a different shape than that from a shallow mark amongst deep neighbors. In other words, there is not a single impulse response function as there is in the linear system shown for comparison.

To better understand the origin and mathematical form of the nonlinear ISI, a simple local-interference model which could be solved analytically was used. In this picture, the reader signal arises from destructive interference between the light reflecting off the groove and light that reflects off the adjacent land between tracks. The electric field returning from a spot centered over the jth pit is given by:

$$E_j = \text{ field from adjacent land } + \text{ field from groove}$$

$$E_j = \tfrac{1}{2} + \tfrac{1}{2}\sum_{k=-n}^{+n} a_k\, e^{i\phi_{j-k}} \qquad (1)$$

where fj is the phase shift due to the depth of pit j, and ak is a finite sequence representing how the beam is distributed on the neighboring pits. If one identifies r_i as the intensity $|E_i|^2$, and w_i as the quantity $\tfrac{1}{2}(1+\cos\phi_i)$— the "S-curve" in this case — one can show that:

$$r_i = \sum_j a_j w_{i-j} - \tfrac{1}{2}\sum_{j,k} a_j a_k \sin^2\left(\frac{\sin^{-1}(2w_{i-j}-1) - \sin^{-1}(2w_{i-k}-1)}{2}\right)$$
$$= \sum_j a_j w_{i-j} - \tfrac{1}{2}\sum_{j,k} a_j a_k \left(w_{i-j} - w_{i-k}\right)^2 + O\left(2w_i - 1\right)^4 \qquad (1)$$

The sequence a_j can now be interpreted as a set of (linear) convolution coefficients. (The MTF and a_j are completely equivalent descriptions of the linear impulse response of the ODDC.) The second term is the nonlinear ISI and arises not from destructive interference between pit and land, but between pit and adjacent or nearby neighboring pit. It acts to lower the reader signal, consistent with Figure 2. The third term represents the remainder of the expansion of the $\sin^2$ term in the equation above.

In certain embodiments, both real data and Fraunhofer diffraction simulations can be better modeled by an expression which is more general than Eq. (1):

$$r_i = \sum_j a_j w_{i-j} - \sum_{j,k} B_{jk} w_{i-j} w_{i-k} \qquad (2)$$

If the nearby symbols $w_{i\pm 1}$, $w_{i\pm 2}$, etc. differ from w_i then the value of r_i differs from w_i and there is ISI. If all w_i in the vicinity are identical then there is no ISI and $r_i = w_i$. To conform to this definition of ISI, the elements a_j sum to unity and the elements B_{jk} sum to zero. The coefficients a_j and B_{jk} ($j,k = -2..+2$, typically) are optimized using a least-squares method to make Eq. (2) match real reader data Eq. (2) can be written concisely as

$$r = a * w - B \bullet w, \quad (3)$$

where r and w now represent the entire sequences, rather than just the ith element as before. The term $a * w$ (the first sum in Eq. (2)) is referred to as a linear convolution, and $B \bullet w$ (the second sum) is called a "nonlinear convolution." The analysis presented here does not depend on the form of the nonlinear convolution. Different formulas which are developed can be implemented by redefining "$\bullet$" in the equations that follow.

The linear part of Eq. (3) is invertible. As long as the ISI is not too severe, one can calculate a sequence of coefficients a^{-1} such that $a^{-1} * (a * w) = w$. Since a can be physically measured or measured using a computer simulation, a^{-1} can be derived from the physical measurements of a. In one embodiment, the reader is preprogrammed with the coefficients of

a. In other embodiments, the coefficients of a are encoded on the disc. Likewise, B can also be physically measured. In the fitting process. the $B \bullet W$ form can not produce effects similar to $a*W$; thus they can be fit separately. B, however. is more difficult to invert. The following discussion shows the nonlinear term B is dealt with in one embodiment using an iterative data recovery method.

In one embodiment, a system is designed with no precompensation ($w_i = x_i$). One example of a post-processing method for such a system which inverts Eq. (3) and recovers the data w_i from the sequence of reader samples r_i. is the following iteration, where successive approximations of the sequence w are calculated:

$$\begin{aligned} w^{(0)} &= a^{-1}*r \\ w^{(1)} &= a^{-1}*r+a^{-1}*\left(B \bullet w^{(0)}\right) \\ &\vdots \\ w^{(n)} &= a^{-1}*r+a^{-1}*\left(B \bullet w^{(n-1)}\right) \qquad \text{until } w^{(n)} \approx w^{(n-1)} \end{aligned} \quad (4)$$

To verify that $w^{(n)}$ does represent recovered data, one can apply the $a*$ operation to both sides of the last line. After rearranging terms, one obtains the expression

$$\begin{aligned} r &= a*w^{(n)} - B \bullet w^{(n-1)} \\ &\approx a*w^{(n)} - B \bullet w^{(n)} \end{aligned} \quad (5)$$

showing that $w^{(n)}$ does satisfy Eq. (3). While this process has been shown to work, the post-processing power required to perform the iterations would need to be included in every disc reader. If the computing power required to perform the iteration is large, it may prove advantageous to do this work as a precompensation.

For this reason, in certain embodiments, a precompensation method is used so that the iteration may be performed once, before the data is sent through the ODDC, simplifying the design of the disc player. In such embodiments, rather than a data recovery method, Eq. (4) is instead interpreted as the precompensation step. If it is specified what the reader signal r should be, then $w^{(n)}$ is the sequence that must be fed to the ODDC in order to achieve that output. If r is constrained to be equal to the original data sequence x, then Eq. (4) represents an algorithm which completely precompensates the data for all ISI. If precompensation is

performed according to this constraint, then the sequence r can be passed on to the modulation decoder with no further processing.

In some embodiments, complete precompensation ($r = x$) may harm the signal to noise ratio, depending on how noise enters the system. In a situation where noise is filtered by the ODDC in the same way as w, it turns out to be unfavorable to amplify some frequency components of x over others, as a^{-1} does. Doing so only forces one to confine the original M discrete levels to a smaller dynamic range to ensure that w never exceeds the dynamic range of the ODDC.

Therefore, from a noise perspective, it is preferable to do the equalization after the ODDC, whereas from a system design view, one may wish to minimize the number of deconvolution coefficients required for post-processing. Fortunately it is possible to compromise by splitting a^{-1} into two parts: a short set of coefficients s can provide the coarse frequency response during post-processing, and a long set $(s*a)^{-1}$ can fine tune the signal at the precompensation step. Since r can be chosen in Eq.(4), it can be required that:

$$s*r = x \qquad (6)$$

The levels that need to be written to disc can be calculated with the following iteration:

$$\begin{aligned}
w^{(0)} &= (s*a)^{-1}*x \\
w^{(1)} &= (s*a)^{-1}*x + a^{-1}*\left(B \bullet w^{(0)}\right) \\
&\vdots \\
w^{(n)} &= (s*a)^{-1}*x + a^{-1}*\left(B \bullet w^{(n-1)}\right) \text{until } w^{(n)} \approx w^{(n-1)}
\end{aligned} \qquad (7)$$

When the iteration converges, a sequence w ($= w^{(n)} \approx w^{(n-1)}$) has been found which satisfies the equation:

$$w = (s*a)^{-1} * x + a^{-1} * (B \bullet w) \qquad (8)$$

from which it follows that

$$\begin{aligned} (s*a)*w &= (s*a)*\left((s*a)^{-1} * x + a^{-1} * (B \bullet w)\right) \\ s*(a*w) &= x + s*(B \bullet w) \\ s*(a*w - B \bullet w) &= x \\ s*r &= x \end{aligned} \qquad (9)$$

In principle, there is no restriction on choosing the deconvolution coefficients s. It is possible to choose to do no precompensation of the linear part by setting $s = a^{-1}$, thus requiring the DSP to use a long set of coefficients. Complete precompensation would correspond to $s = (\ldots 0\ 0\ 1\ 0\ 0 \ldots)$. In one embodiment, a 10% fluctuation due to precompensation is preferred, decreasing the available dynamic range by approximately 10%. It is preferable that the precompensation gain change over its frequency range by a total of less than 20%. A change of less than 10% is more preferred, and a change of less than 5% is most preferred.

Thus, a method of compensating for both linear and nonlinear intersymbol interference effects has been described. Precompensation is shown for the nonlinear effects and for portions of the linear effects which would require a large amount of computational resources to deal with on the reader side.

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are may alternative ways of implementing both the process and apparatus of the present invention. For example, it would be possible to use an ablative medium instead of photoresist. Portions of the ablative medium would actually be removed by the incident laser energy without development. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

CLAIMS

WHAT IS CLAIMED IS:

1. A method of fabricating a digital optical disc master comprising:

providing a disc having a substrate which is coated with a layer of photoresist material;

determining at least three discrete digital data levels to be stored at pit locations on said disc;

determining thicknesses of the photoresist material relative to the surface of the photoresist material which will correspond to each discrete digital data level;

determining doses of laser beam energy corresponding to each discrete digital data level which expose the photoresist material to an extent that causes the thickness of the photoresist material after exposure and development to match the thickness corresponding to each discrete digital data level;

exposing portions of the layer of photoresist material to each of the doses of laser beam energy; and

developing the photoresist material so that the portions of the photoresist exposed to each of the doses of laser beam energy have a thickness which corresponds to the discrete digital data level which is stored on the portion of photoresist.

2. A method as recited in claim 1 wherein the photoresist is positive photoresist.

3. A method as recited in claim 1 wherein the photoresist is negative photoresist.

4. A method as recited in any of the above claims wherein exposing portions of the layer of photoresist to each of the doses of laser beam energy includes varying the laser beam power.

5. A method as recited in claim 1 or claim 2 or claim wherein exposing portion of the layer of photoresist to each of the doses of laser beam energy includes exposing each portion of the layer of photoresist to the laser for substantially the same amount of time.

6. A method as recited in any of the above claims wherein exposing portions of the layer of photoresist to each of the doses of laser beam energy includes exposing portions of the layer of photoresist to the laser for different time periods and wherein each different time period corresponds to a dose of laser beam energy.

7. A method of fabricating a digital optical disc master comprising:

determining at least three discrete digital data levels;

providing a disc surface material;

determining displacement distances in the disc surface material which correspond to each discrete digital data level;

providing a laser beam;

determining doses of laser beam energy which displace the disc surface material by the displacement distances which correspond to each discrete digital data level; and

exposing portions of the disc surface to each of the doses of laser beam energy so that the surface of the disc is displaced according to the displacement distances which correspond to each discrete digital data level.

8. A method as recited in claim 1 wherein the thicknesses of photoresist material which corresponds to each data level range from about 0 nm relative to the surface of the photoresist material to about 150 nm relative to the surface of the photoresist material.

9. A method as recited in claim 1 wherein the difference in the thicknesses of photoresist material which corresponds to different discrete data levels is less than about 40 nm.

10. A method as recited in claim 1 wherein the maximum range of thicknesses of the photoresist material does not exceed a thickness range which is approximately 200 nm.

11. A method as recited in claim 1 wherein the maximum range of thicknesses of the photoresist material does not exceed a thickness range which is approximately 1/4 of a wavelength of the light which is to be used to read said thicknesses.

12. A method as recited in claim 1 further including determining a development time for said layer of photoresist material, said development time being determined so that the thickness of the photoresist material in an area of said disc wherein said photoresist is only partially removed has a thickness relative to the surface of the disc corresponding to a discrete data level in a manner which enables a determination of the thickness of said photoresist relative to the surface of the disc at a single point in said area to provide a determination of said discrete data level.

13. A method of forming a digital optical disc master from a disc having a substrate coated with a photoresist coating, the method comprising:

irradiating the surface of the photoresist material with a laser beam at a multiplicity of pit locations over the substrate to cause a level of the photoresist material to react to the radiation so that the level of reacted photoresist material at each of said multiplicity of pit locations corresponds to a predetermined discrete digital threshold level relative to the surface of the disc and wherein the dose of radiation applied during the irradiation of the surface is calculated to cause the photoresist material to react to a level corresponding to the predetermined discrete digital threshold level relative to the surface of the photoresist; and

developing the photoresist material to form a multiplicity of pits, there being at least three discrete predetermined pit levels formed during the irradiation, each discrete pit level being formed to a predetermined distance relative to the surface of the photoresist

corresponding to the predetermined discrete digital threshold level relative to the surface of the photoresist,

whereby each pit location has the ability to store more than one bit of digital information according to the correspondence of the pit level with the predetermined discrete digital threshold level relative to the surface of the photoresist.

14. A method as recited in claim 13 wherein the predetermined discrete digital threshold levels consist of in the range of 3 to 8 levels.

15. A method as recited in claim 13 wherein the predetermined discrete digital threshold levels consist of in the range of 3 to 64 levels.

16. A method as recited in claim 13 wherein lands are provided between adjacent pits.

17. A method as recited in claim 13 wherein the dose of radiation applied during the irradiation of the surface is calculated in a manner which compensates for non-linearities in the relationship between the dose of radiation and the level of reacted photoresist material.

18. A method as recited in claim 13 wherein the predetermined discrete digital threshold levels are set at approximately equally distant step levels.

19. An optical disk containing stored digital information manufactured according to A method as recited in claim 13.

20. A method as recited in claim 13 wherein the predetermined discrete digital threshold levels relative to the surface of the disc range from a displacement of about 0 nm relative to the surface of the disc to a displacement of about 150 nm relative to the surface of the disc.

21. A method as recited in claim 13 wherein the difference in the level of reacted photoresist material at each of said multiplicity of pit locations which corresponds to a predetermined discrete digital threshold level relative to the surface of the disc is less than about 40 nm.

22. A method as recited in claim 13 wherein the maximum range of the levels of reacted photoresist material does not exceed approximately 200 nm.

23. A method as recited in claim 13 wherein the maximum of the level of reacted photoresist material does not exceed approximately 1/4 of a wavelength of the light which is to be used to read said pits.

24. A method as recited in claim 13 further including determining a development time for said photoresist material, said development time being determined so that the thickness of the photoresist material in an area of said disc wherein said photoresist is only partially removed has a thickness relative to the surface of the disc corresponding to a discrete data level in a manner which enables a determination of the thickness of said photoresist relative to the surface of the disc at a single point in said area to provide a determination of said discrete data level.

25. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol linear transfer function, said intersymbol linear transfer function substantially describing a linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol linear transfer function being convolved with a write signal to produce a linearly transformed portion of the optically detected read signal;

determining an inverse linear transfer function of the intersymbol linear transfer function, said inverse linear transfer function having the property of canceling the effect of convolving the intersymbol linear transfer function with the write signal; and

convolving the optically detected read signal with the inverse linear transfer function;

whereby the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled by the convolution of the optically detected read signal with the inverse linear transfer function.

26. A method as recited in claim 25 wherein convolving the optically detected read signal with the inverse linear transfer function further includes inputting the optically detected read signal to a DSP filter having a transfer function which is substantially the inverse linear transfer function.

27. A method as recited in claim 25 wherein convolving the optically detected read signal with the inverse linear transfer function further includes inputting the optically detected read signal to a neural network filter having a transfer function which is substantially the inverse linear transfer function.

28. A method as recited in claim 25 further including using a Viterbi decoder to determine the maximum likelihood stored signal given the optically detected read signal.

29. A method as recited in claim 26 further including referencing the frequency response of the DSP filter to the data sampling clock.

30. A method as recited in claim 27 further including referencing the frequency response of the neural network filter to the data sampling clock.

31. A method as recited in claim 25 wherein the optically detected read signal is obtained by sampling the disc at a constant angular velocity.

32. A method as recited in claim 27 wherein the optically detected read signal is obtained by sampling the disc at a constant angular velocity.

33. A method as recited in claim 29 wherein the optically detected read signal is obtained by sampling the disc at a constant angular velocity.

34. A method as recited in claim 25 as applied to a pit depth modulated optical disc system.

35. A method as recited in claim 26 as applied to a pit depth modulated optical disc system.

36. A method as recited in claim 25 as applied to a CD optical disc system.

37. A method as recited in claim 25 as applied to a DVD optical disc system.

38. A method as recited in claim 25 as applied to an MO optical disc system.

39. A method as recited in claim 25 as applied to an optical disc system that is a phase change system.

40. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol linear transfer function, said intersymbol linear transfer function substantially describing the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol linear transfer function being convolved with a write signal to produce a linearly transformed portion of the optically detected read signal

determining an inverse linear transfer function of the intersymbol linear transfer function, said inverse linear transfer function having the property of canceling the effect of convolving the intersymbol linear transfer function with the write signal;

dividing the inverse linear transfer function into a short portion and a long portion;

convolving the write signal with a precompensation transfer function, the precompensation transfer function being substantially the inverse of the long portion of the inverse linear transfer function; and

convolving the optically detected read signal with the short portion of the inverse linear transfer function;

whereby the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

41. A method as recited in claim 40 wherein convolving the optically detected read signal with the short portion of the inverse linear transfer function is performed using an analog circuit.

42. A method as recited in claim 40 wherein convolving the optically detected read signal with the short portion of the inverse linear transfer function is performed using a digital circuit.

43. A method as recited in claim 40 wherein the gain of the precompensation transfer function changes over its frequency range by a total of less than 20%

44. A method as recited in claim 40 wherein the gain of the precompensation transfer function changes over its frequency range by a total of less than 10%

45. A method as recited in claim 40 wherein the gain of the precompensation transfer function changes over its frequency range by a total of less than 5%

46. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol nonlinear transfer function, said intersymbol nonlinear transfer function substantially describing the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol nonlinear transfer function being nonlinearly convolved with a write signal to produce a nonlinearly transformed portion of the optically detected read signal

determining an inverse nonlinear transfer function of the intersymbol nonlinear transfer function, said inverse nonlinear transfer function having the property of canceling the effect of nonlinearly convolving the intersymbol nonlinear transfer function with the write signal; and

nonlinearly convolving the write signal with a precompensation transfer function, the precompensation transfer function being substantially the same as the inverse nonlinear transfer function;

whereby the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

47. A method as recited in claim 46 wherein determining an inverse nonlinear transfer function of the intersymbol nonlinear transfer function is accomplished by an iterative method.

48. A method as recited in claim 47 wherein the iterative method is substantially described by the following equations:

$$w^{(0)} = a^{-1} * r$$
$$w^{(1)} = a^{-1} * r + a^{-1} * \left(B \bullet w^{(0)}\right)$$
$$\vdots$$
$$w^{(n)} = a^{-1} * r + a^{-1} * \left(B \bullet w^{(n-1)}\right)$$

until $w^{(n)} \approx w^{(n-1)}$.

49. An optical disc data track precompensated for the effects of nonlinear intersymbol interference comprising:

a data track formed according to a write signal, the write signal being determined to precompensate for the effects of nonlinear intersymbol interference, the effects of nonlinear intersymbol interference being substantially described by an intersymbol nonlinear transfer function, said intersymbol nonlinear transfer function being nonlinearly convolved with a write signal to produce a nonlinearly transformed portion of the optically detected read signal; the precompensation being substantially performed by nonlinearly convolving an inverse nonlinear transfer function of the intersymbol nonlinear transfer function, said inverse nonlinear transfer function having the property of canceling the effect of nonlinearly convolving the intersymbol nonlinear transfer function with the write signal;

whereby the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

50. A method of compensating for intersymbol interference on an optical disc comprising:

creating a first pit having a first depth, said first depth corresponding to a digital data level stored at the location of the first pit; and

creating a second pit having a second depth, said second depth corresponding to the same digital data level as the digital data level stored at the location of the first pit, wherein the difference between the first depth and the second depth precompensates for the difference between a first intersymbol interference between the first pit and neighboring pits that are located in the vicinity of the first pit and a second intersymbol interference between the second pit and neighboring pits that are located in the vicinity of the second pit;

whereby compensation is made for intersymbol interference.

51. A method as described in claim 50 wherein the difference between the first depth and the second depth precompensates for linear effects resulting from the difference between a first intersymbol interference between the first pit and neighboring pits that are located in the vicinity of the first pit and a second intersymbol interference between the second pit and neighboring pits that are located in the vicinity of the second pit.

52. A method as described in claim 50 wherein the difference between the first depth and the second depth precompensates for nonlinear effects resulting from the difference between a first intersymbol interference between the first pit and neighboring pits that are located in the vicinity of the first pit and a second intersymbol interference between the second pit and neighboring pits that are located in the vicinity of the second pit.

53. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol nonlinear transfer function, said intersymbol nonlinear transfer function substantially describing the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol nonlinear transfer function being nonlinearly convolved with a write signal to produce a nonlinearly transformed portion of the optically detected read signal

determining an inverse nonlinear transfer function of the intersymbol nonlinear transfer function, said inverse nonlinear transfer function having the property of canceling the effect of nonlinearly convolving the intersymbol nonlinear transfer function with the write signal; and

dividing the inverse nonlinear transfer function into a first portion and a second portion; and

nonlinearly convolving the write signal with a precompensation transfer function, the precompensation transfer function being substantially the inverse of the first portion of the inverse nonlinear transfer function; and

nonlinearly convolving the optically detected read signal with the second portion of the inverse nonlinear transfer function;

whereby the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

54. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol nonlinear transfer function, said intersymbol nonlinear transfer function substantially describing the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol nonlinear transfer function being nonlinearly convolved with a write signal to produce a nonlinearly transformed portion of the optically detected read signal

determining an inverse nonlinear transfer function of the intersymbol nonlinear transfer function, said inverse nonlinear transfer function having the property of canceling the effect of nonlinearly convolving the intersymbol nonlinear transfer function with the write signal; and

nonlinearly convolving the optically detected read signal with the inverse nonlinear transfer function;

whereby the nonlinear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

55. A method of compensating for intersymbol interference on an optical disc comprising:

measuring an intersymbol linear transfer function, said intersymbol linear transfer function substantially describing the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc, said intersymbol linear transfer function being convolved with a write signal to produce a transformed portion of the optically detected read signal;

determining an inverse linear transfer function of the intersymbol linear transfer function, said inverse linear transfer function having the property of canceling the effect of convolving the intersymbol nonlinear transfer function with the write signal; and

linearly convolving the write signal with a precompensation transfer function, the precompensation transfer function being substantially the same as the inverse linear transfer function;

whereby the linear portion of the effect of intersymbol interference on an optically detected read signal from an optical disc is canceled.

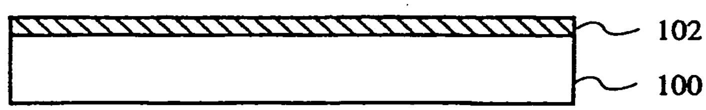

FIGURE 1A

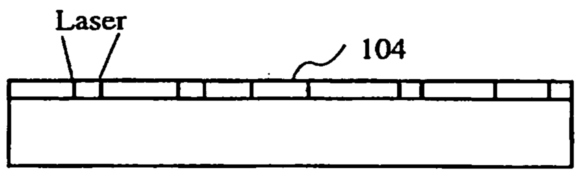

FIGURE 1B

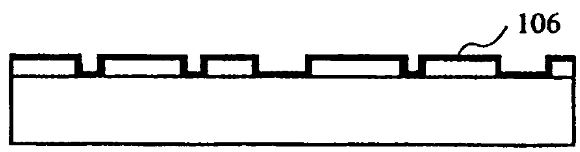

FIGURE 1C

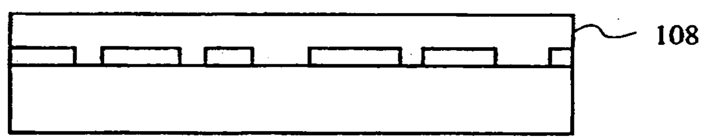

FIGURE 1D

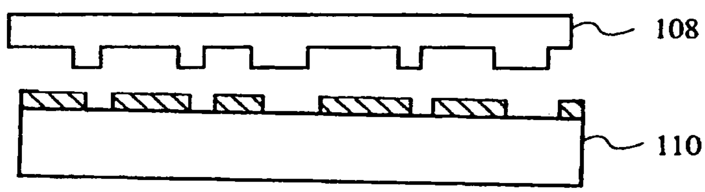

FIGURE 1E

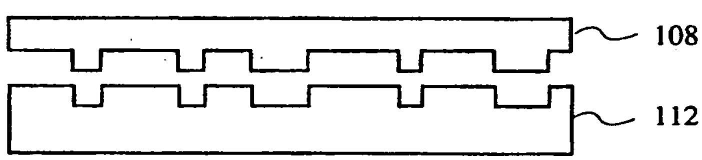

FIGURE 1F

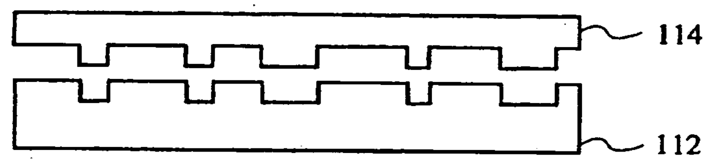

FIGURE 1G

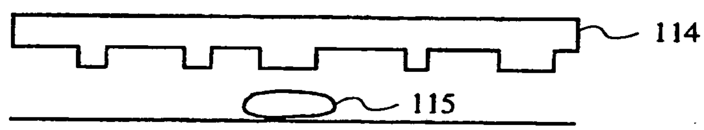

FIGURE 1H

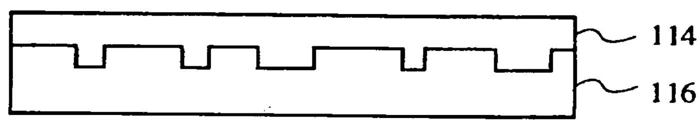

FIGURE 1I

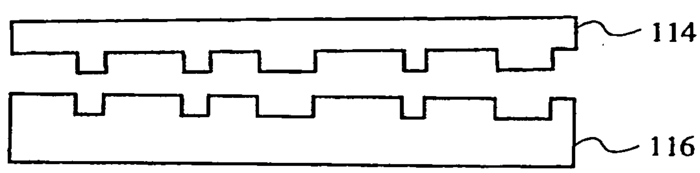

FIGURE 1J

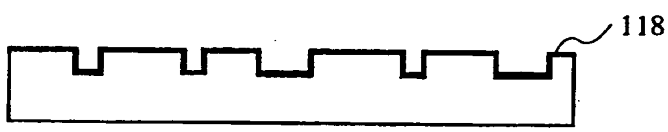

FIGURE 1K

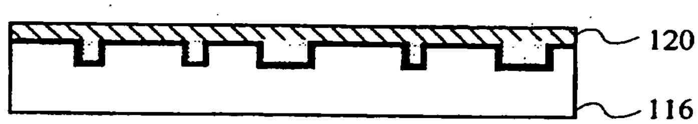

FIGURE 1L

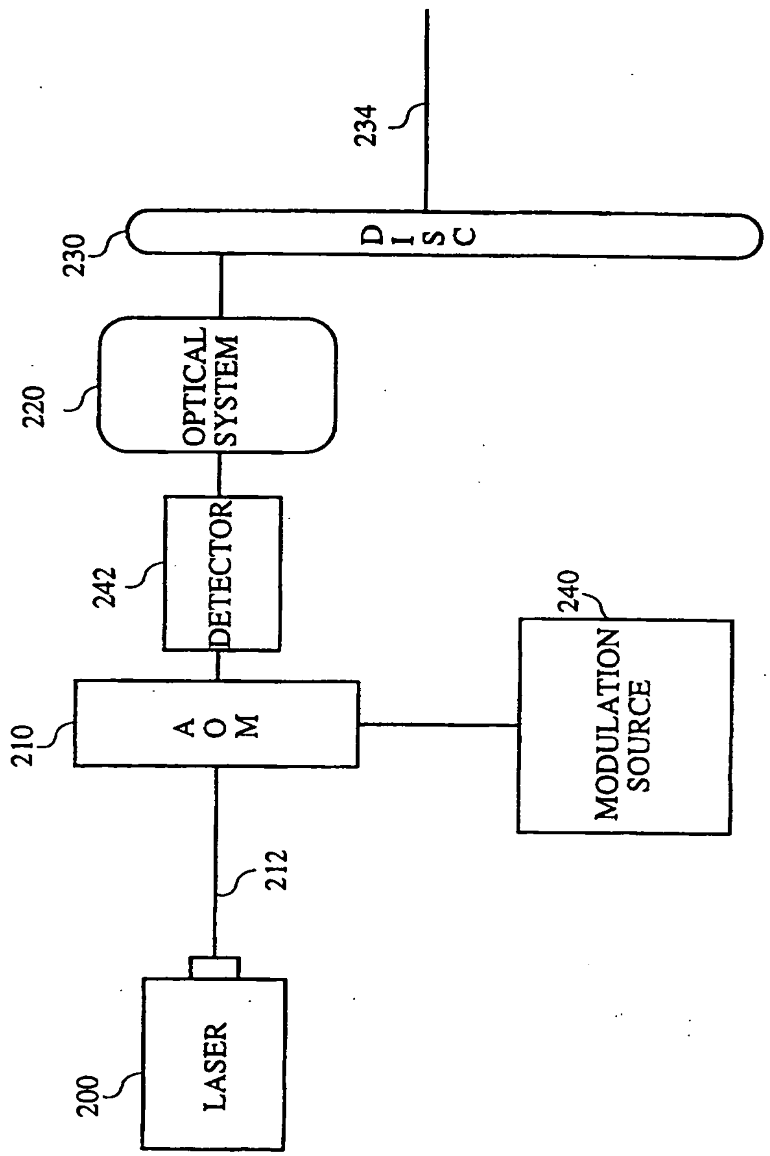
234
230
DISC
220
OPTICAL SYSTEM
242
DETECTOR
240
MODULATION SOURCE
210
AOM
212
200
LASER

FIGURE 2

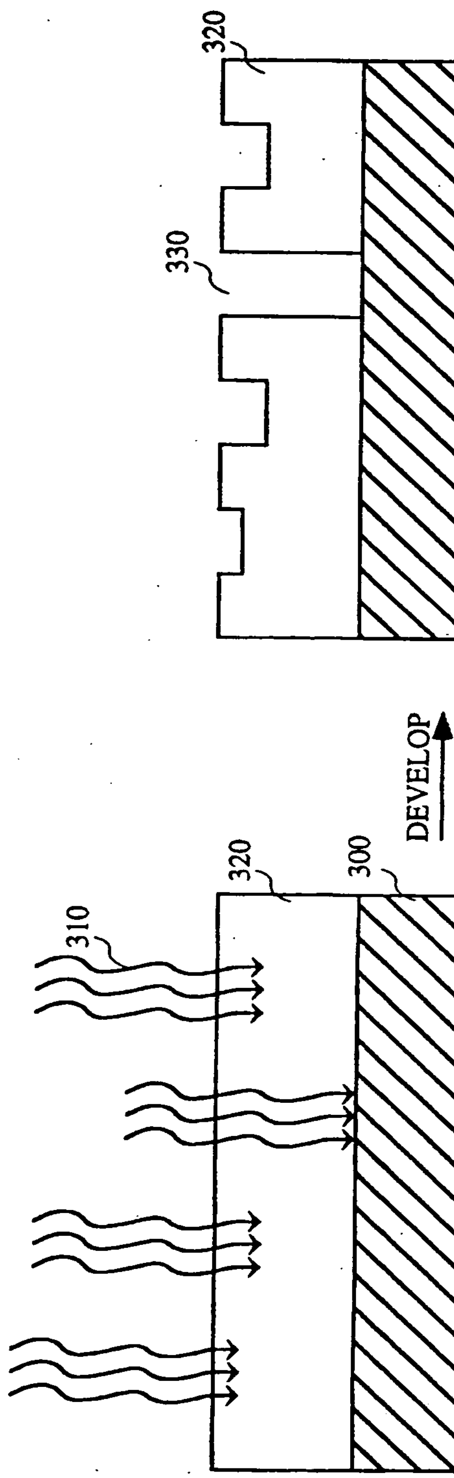

FIGURE 3

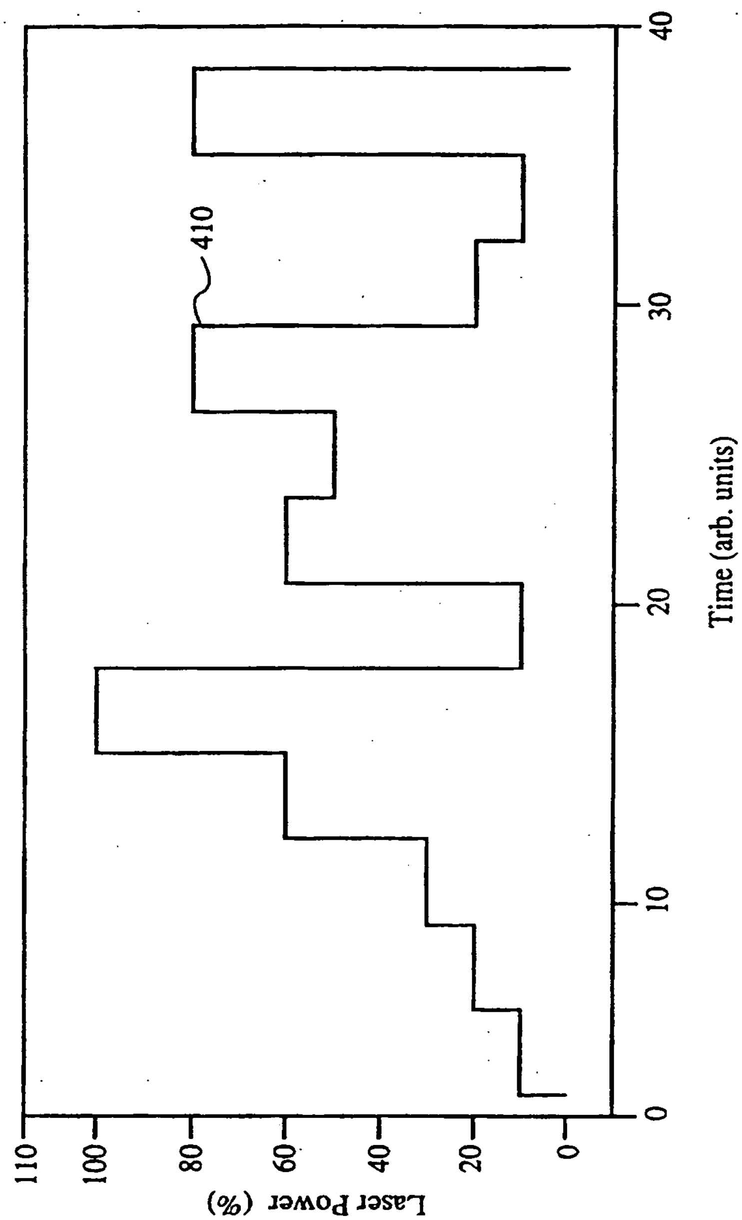

FIGURE 4

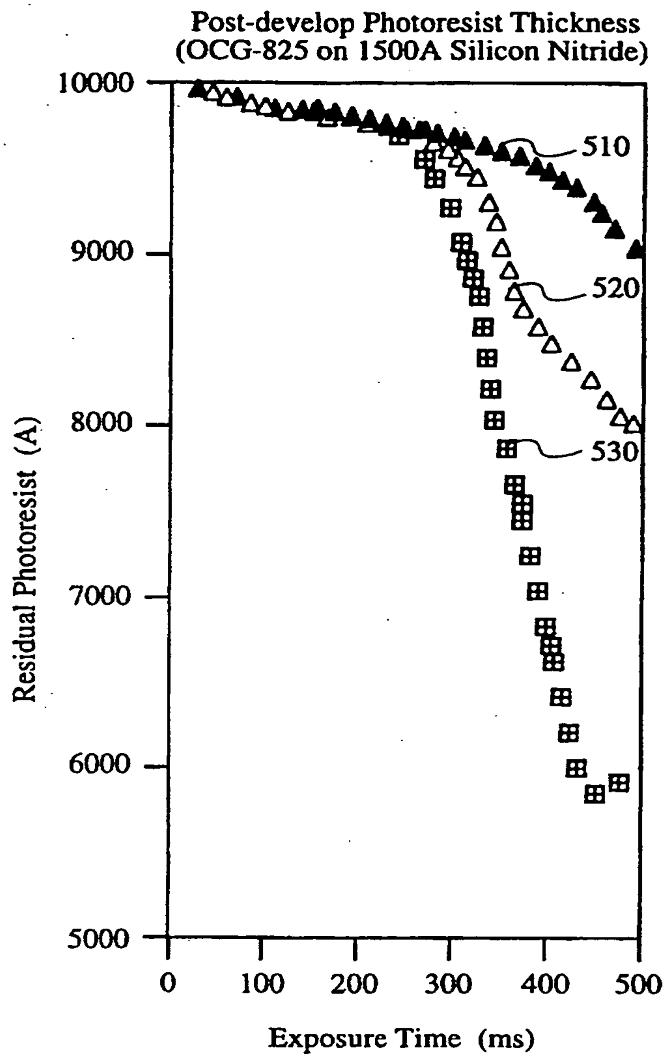
Post-develop Photoresist Thickness
(OCG-825 on 1500A Silicon Nitride)
10000
9000
8000
7000
6000
5000
Residual Photoresist (A)
0
100
200
300
400
500
Exposure Time (ms)
510
520
530

FIGURE 5A

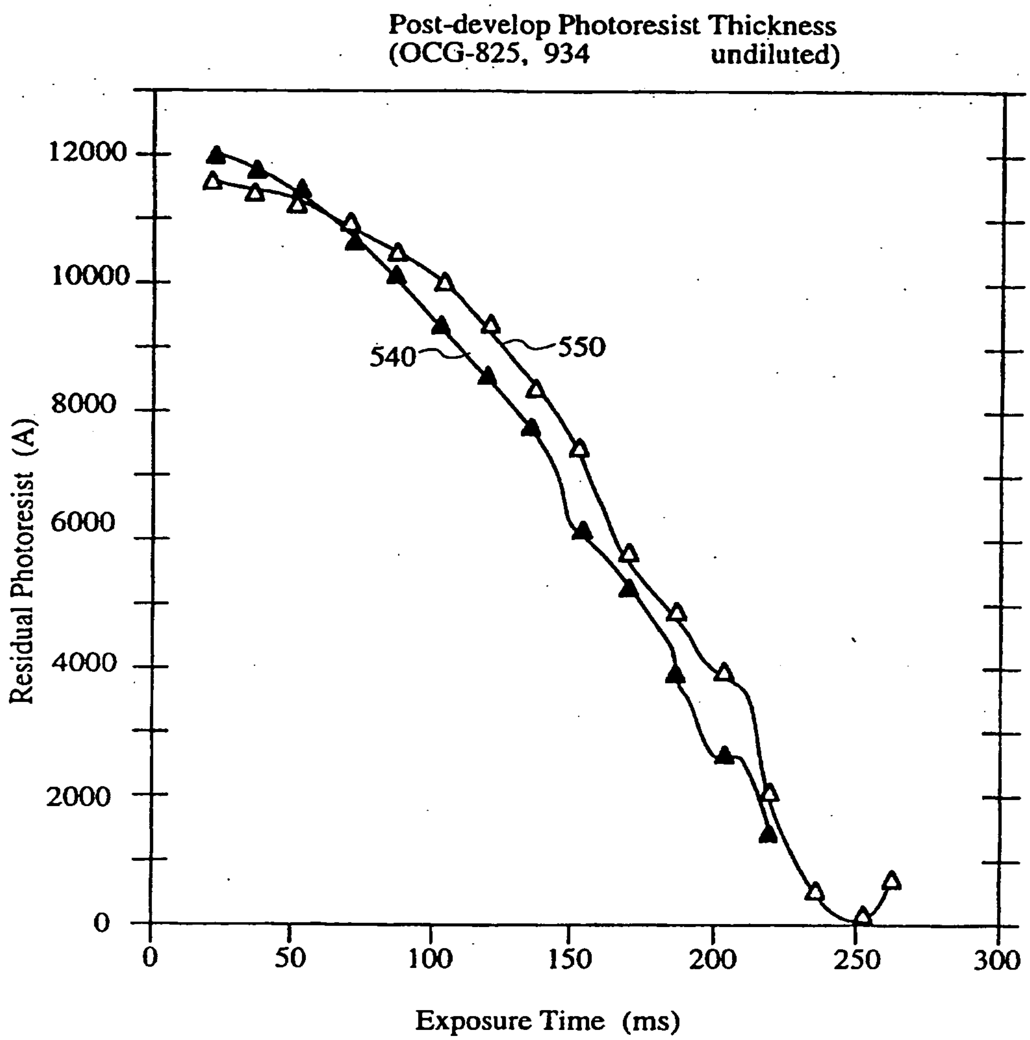
Post-develop Photoresist Thickness
(OCG-825, 934 undiluted)
Residual Photoresist (A)
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
Exposure Time (ms)
540
550

FIGURE 5B

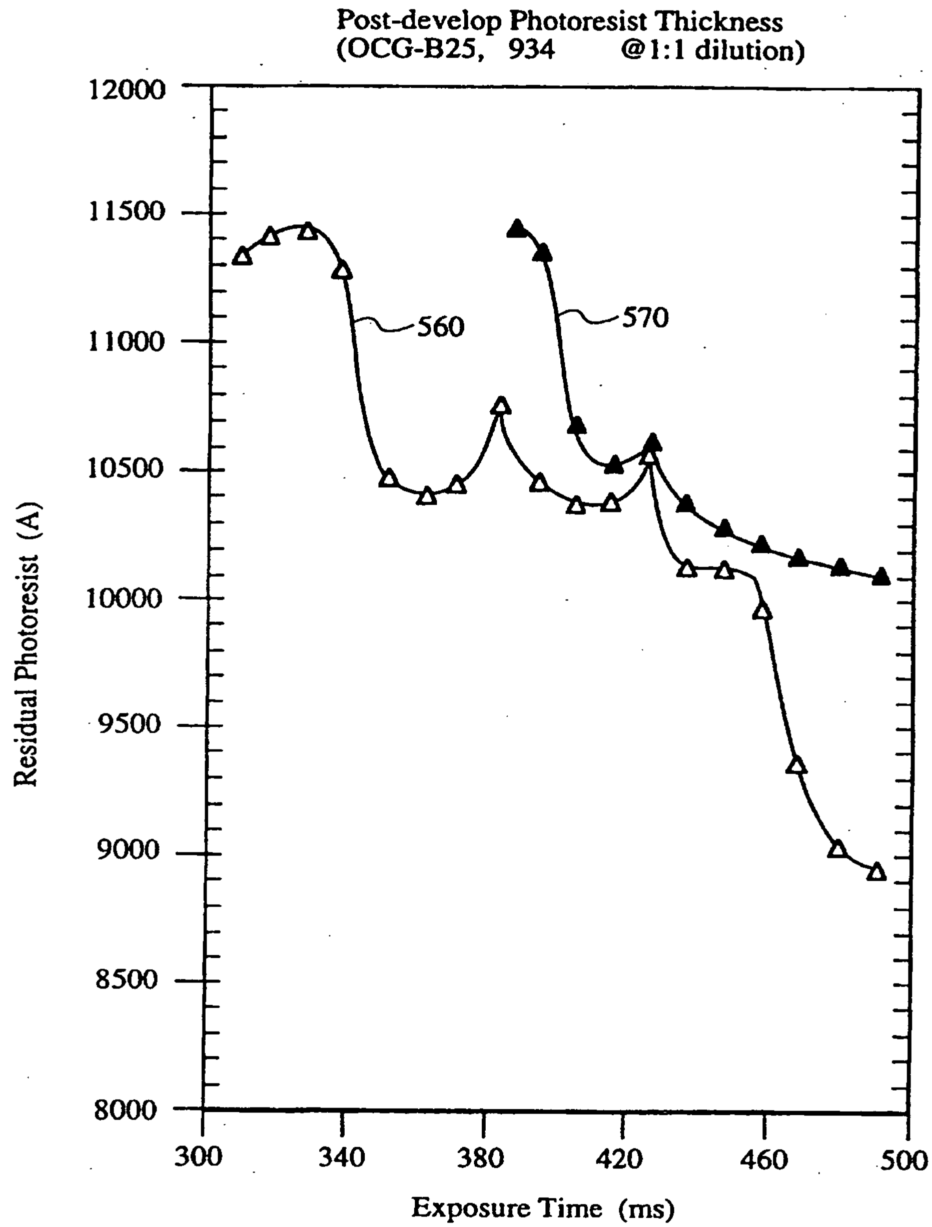
Post-develop Photoresist Thickness
(OCG-B25, 934 @1:1 dilution)
12000
11500
11000
10500
10000
9500
9000
8500
8000
Residual Photoresist (A)
560
570
300
340
380
420
460
500
Exposure Time (ms)

FIGURE 5C

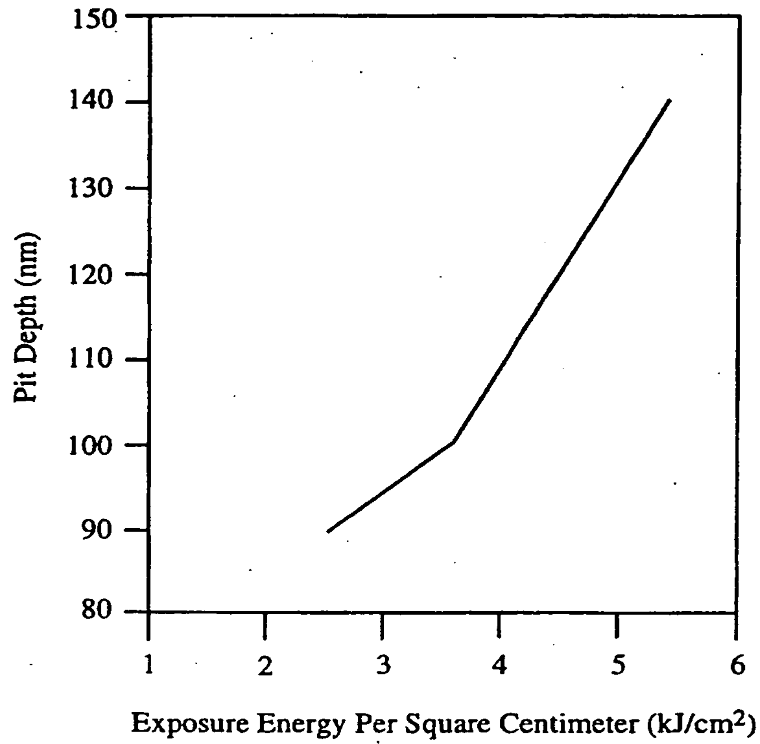
150
140
130
120
110
100
90
80
Pit Depth (nm)
1
2
3
4
5
6
Exposure Energy Per Square Centimeter (kJ/cm2)

FIGURE 6

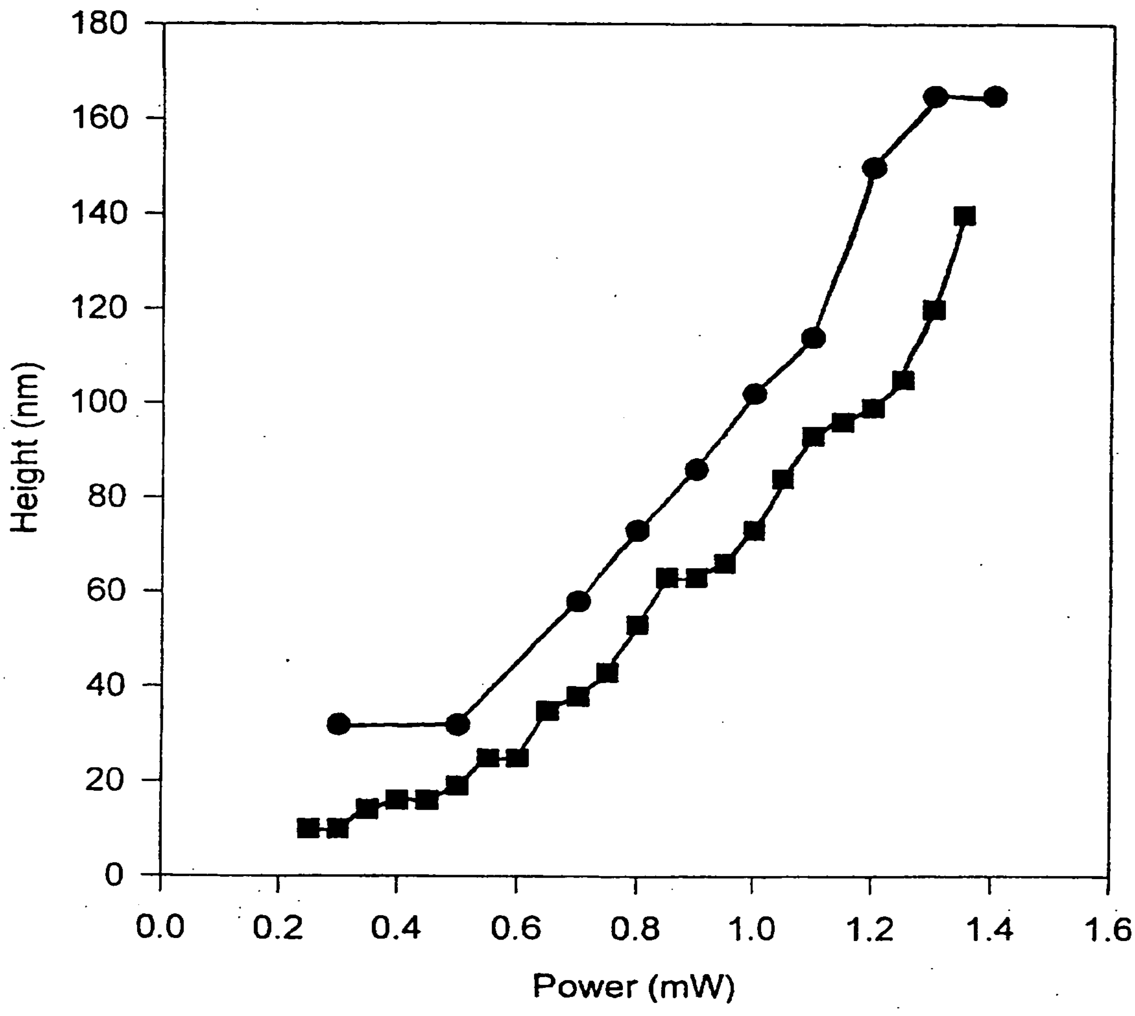
180
160
140
120
100
80
60
40
20
0
Height (nm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Power (mW)

FIGURE 7

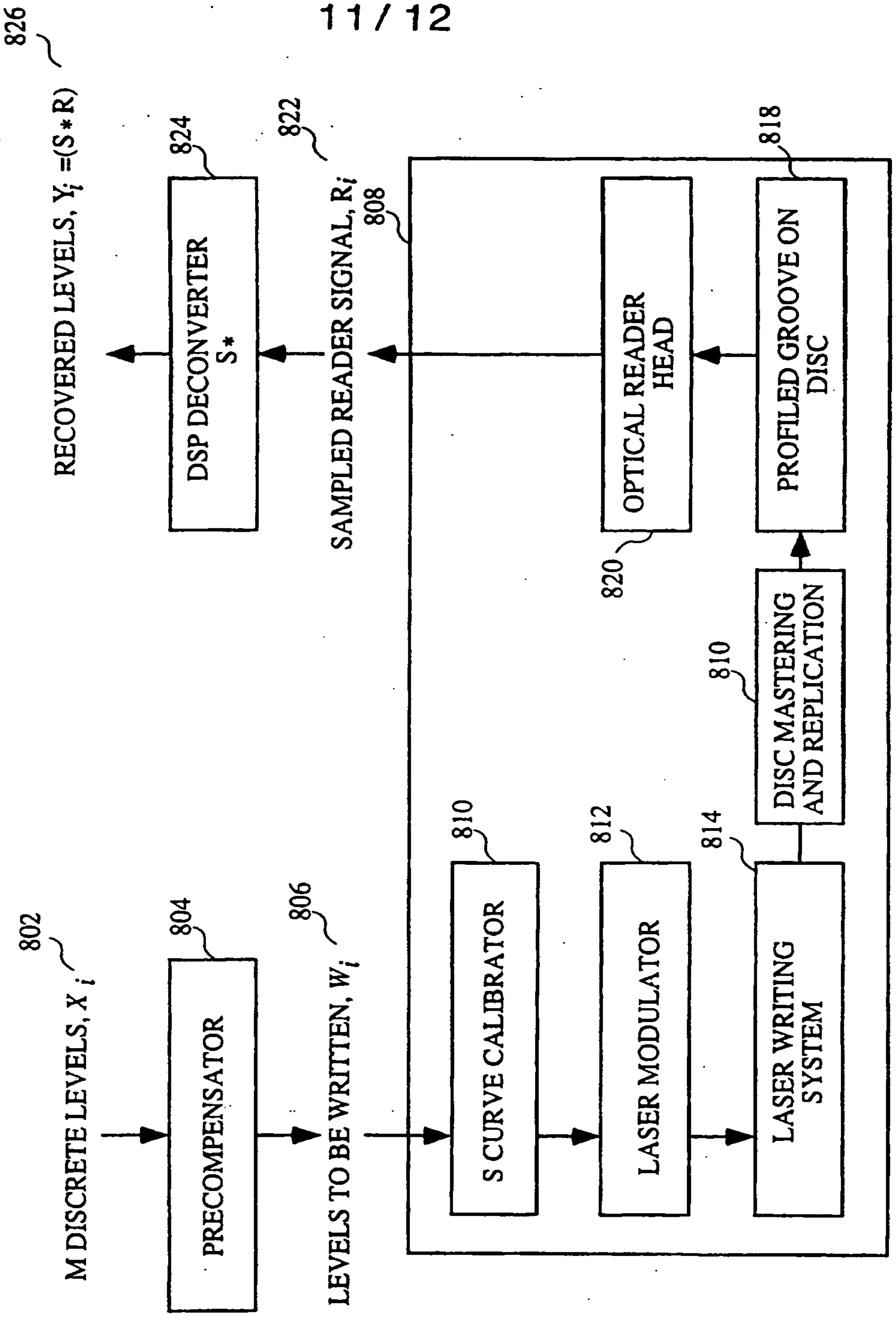
M DISCRETE LEVELS, X_i
802
PRECOMPENSATOR
804
LEVELS TO BE WRITTEN, W_i
806
S CURVE CALIBRATOR
810
LASER MODULATOR
812
LASER WRITING SYSTEM
814
DISC MASTERING AND REPLICATION
810
PROFILED GROOVE ON DISC
818
OPTICAL READER HEAD
820
808
SAMPLED READER SIGNAL, R_i
822
DSP DECONVERTER $S*$
824
RECOVERED LEVELS, $Y_i = (S*R)$
826

FIGURE 8

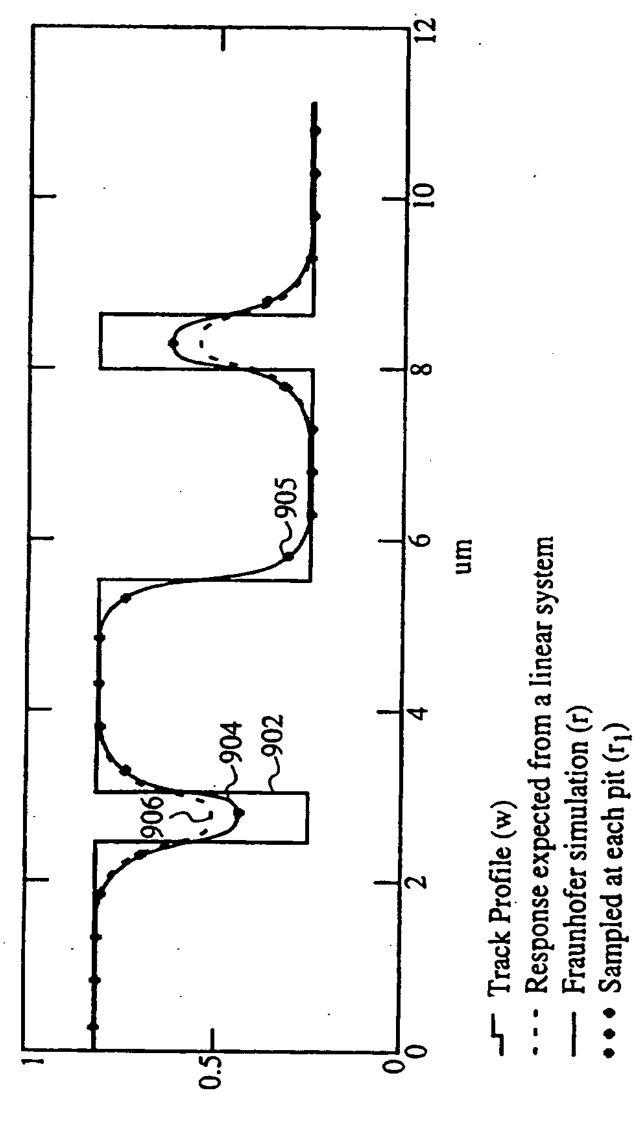
0
0.5
1
0
2
4
6
8
10
12
um
902
904
905
906
Track Profile (w)
Response expected from a linear system
Fraunhofer simulation (r)
Sampled at each pit (r_1)

FIGURE 9